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THE EFFECTS OF DEICING SALTS ON WATER
CHEMISTRY IN PINHOOK BOG, INDIANA¹Douglas A. Wilcox²

ABSTRACT: A five-year study was conducted to identify the effects of road salt intrusion on the water chemistry of Pinhook Bog following operation of an uncovered salt storage pile adjacent to the bog for ten years. A distinct pattern of elevated salt concentrations was observed in the interstitial waters of the surface peat that corresponded to observed alterations in the bog vegetation. Yearly mean salt concentrations as high as 468 mg/l sodium and 1215 mg/l chloride were recorded in the plant root zone of the peat mat. The salt concentrations decreased significantly each year from 1979 to 1981 throughout the impacted area. Some increases of a lesser magnitude occurred in 1982 and 1983. Analysis of salt movements suggested that vertical transport by water movement was responsible for concentration changes. The major declines in salt levels occurred in the spring following snowmelt and heavy precipitation events. Evapotranspiration during periods of drought resulted in the gradual increases in surface peat salt concentrations. Diverted highway runoff was shown to be the major continuing source of sodium chloride contamination and was the likely source of the elevated calcium, magnesium, potassium, bicarbonate, and pH levels also observed in the impacted area.

(KEY TERMS: road-salt runoff; bog water chemistry; deicing salts; sodium chloride; salt migration; peatlands.)

is virtually unknown. A limited study of the problems associated with deicing salt storage adjacent to Pinhook Bog in northwestern Indiana was conducted by Ten Ech Environmental Consultants (1975). However, the focus of that study was on the regional groundwater system and did not reflect the levels or patterns of salt contamination within the isolated bog basin that were observed during my initial investigations at the site. Therefore, a comprehensive study of water chemistry changes in the impacted portion of Pinhook Bog was conducted as part of a larger study including vegetation analyses (Wilcox, 1986). The water chemistry study was undertaken to determine the pattern and movement of elevated salt concentrations within the bog basin. Specific objectives of the study were to determine water chemistry differences between impacted and unimpacted areas, to investigate salt movements and concentration changes that may be occurring with time, and to identify continuing sources of salt input into the bog.

INTRODUCTION

The use of deicing salts on highways is common in the northerly climates and has resulted in impacts to a number of ecosystems and their components. Stratification and meromixis in lakes have been attributed to road salt runoff (Judd, 1970; Bubeck, *et al.*, 1971), as have increased sodium and chloride concentrations in rivers (Peters and Turk, 1981), ponds (Hutchinson, 1970), and groundwater (Hutchinson, 1970; Pollock, *et al.*, 1973). Associated effects have been documented for benthic invertebrates (Crowther and Hynes, 1977; Molles, 1980) and fish and wildlife (Trainer and Karstad, 1960; Hanes, *et al.*, 1970; EPA, 1971). The impacts to soils (Hutchinson and Olson, 1967; Prior and Berthouex, 1967; Hutchinson, 1970) and vegetation (reviewed by Hanes, *et al.*, 1970; Field, *et al.*, 1973; Succoff, 1975; Hanes, *et al.*, 1976) along roadsides have been studied extensively.

Although peatlands are also common to the north, the effects of deicing salts on water chemistry in a bog ecosystem

STUDY AREA

Pinhook Bog is located in LaPorte County in northwestern Indiana (Figure 1) and occupies an ice block depression in the Valparaiso moraine, deposited by the retreating Wisconsin age glacier (Reshkin, 1981). Surrounded by a shallow, narrow moat, the 44-hectare wetland area is characterized by acidic, weakly-mineralized water conditions, a floating *Sphagnum* mat, and numerous open water ponds. The characteristic bog vegetation includes *Sphagnum* mosses, sundew, pitcherplant, leatherleaf, highbush blueberry, and tamarack. The wetland has been described as the finest bog in Indiana (Sullivan, 1965; Lindsey, *et al.*, 1969).

Preservation of Pinhook Bog was jeopardized in 1963 when the Indiana Toll Road Commission established an uncovered sodium chloride road-salt storage pile on an embankment above the bog. The road-salt was intended for use as a deicing compound on the Indiana Toll Road (I-80/90) which

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forms the southern boundary of the bog. Salt-water runoff from the highway and the salt storage site began to create environmental problems at Pinhook Bog that were first noted in the late 1960's. The most obvious impact was the death of resident plant species such as tamarack and the replacement by invading species (cattail) in a 2-ha area of the bog. Numerous complaints about the runoff caused the Toll Road Commission to construct a domed enclosure for the salt pile in 1972. A diversion ditch emptying into a salt-water retention pond was constructed around the salt pile operation to prevent further runoff from entering the bog. However, plowing of snow in the winter sometimes blocked this ditch, causing it to overflow and drain into the bog. This problem was alleviated when salt storage at the site was discontinued following the winter of 1980-1981.

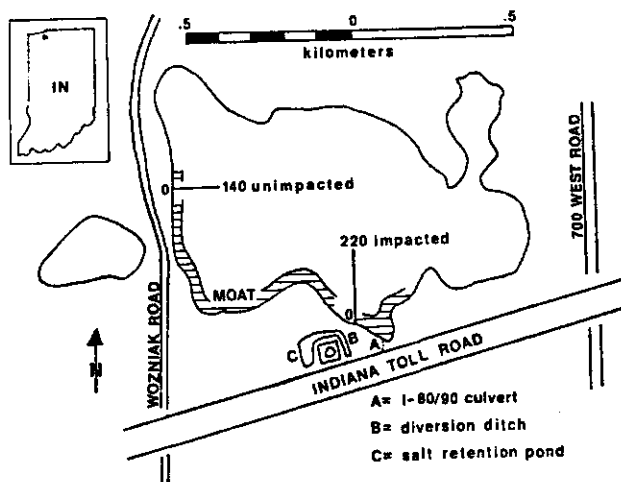


Figure 1. Map of Study Site at Pinhook Bog, LaPorte Co., Indiana, Showing Impacted and Unimpacted Transects.

Despite these measures to protect the bog from salt-laden water, drainage from approximately one kilometer of 4-lane highway still reached the bog watershed through natural surface runoff and culvert diversion. An estimated 113,000 kg of deicing salts were applied to this section of highway each year between 1963 and 1972. During recent years, application of deicing salts has increased to meet the demand for clear, dry pavement. However, mild winters from 1979-80 through 1982-83 resulted in lower application rates than in previous years. Total chloride inputs to Pinhook Bog during the ten-year period when the salt pile was uncovered included 38,000 kg by atmospheric precipitation on the drainage basin, 409,000 kg from Toll Road salting, and 2,337,000 kg through runoff and infiltration from the salt pile (Ten Ech, 1975).

To help preserve the quality of Pinhook Bog, Congress included the peatland and most of its 215-ha watershed within the boundaries of Indiana Dunes National Lakeshore as part of the 1966 and 1976 authorization bills.

METHODS

A south-north impacted transect line was established, extending 220 m from a randomly selected point at the base of the salt storage area to a point one-third of the way across the bog to the north (Figure 1). The transect traversed a portion of the moat, areas of bog mat dominated by cattails, and areas dominated by blueberries, huckleberries, and tamarack. A west-east unimpacted transect line was also established, extending 140 m from a randomly selected point on the western edge to an open-water pond to the east. The unimpacted transect was terminated at 140 m because of the pond and because vegetation east of the pond had been altered by visitor trampling. Vegetation communities similar to the natural areas of the impacted transect were well represented in the 140 m unimpacted transect (Wilcox, 1986).

Water samples for chemical analysis were collected bi-weekly (June-October, 1979-1983) from shallow wells or shallow and deep well pairs developed at points along the impacted transect corresponding to 0, 35, 50, 70, 90, 125, 140, 150, 170, and 220 meters from the base of the salt storage area (designated PB-0, PB-35, etc.). The PB-0 and PB-35 sites represent locations on either side of the moat. Sites PB-90, PB-125, and PB-220 were originally chosen on the basis of vegetation gradients, with additional wells sited as needed to fill the gaps. Two more shallow wells were established adjacent to PB-125 (15 m east and west) to detect lateral movements of salt. Deep and shallow wells are differentiated by a *d* or *s* designation following the well site identification (e.g., PB-35d). Along the unimpacted transect, the well sites were spaced 20 m apart. Unimpacted transect wells were sampled monthly, June-October, 1980-1982.

Shallow wells to sample interstitial *Sphagnum* mat water were constructed from lengths of 10 cm diameter perforated plastic field drainage tile. The lower ends were sealed with plastic film and inserted into half meter deep holes cut into the mat with a posthole digger. Deep wells to sample the open water layer beneath the mat consisted of 5 cm diameter stainless steel drive points with PVC casing. These wells were hand driven to the required depth (approximately 3m) and were screened for 90 cm. Coring devices were used to determine a portion of the bog stratigraphy and verify that the screens were in an open water zone. Two intermediate depth wells were installed at PB-50 in 1981. All deep and shallow wells were pumped before and during sampling with a hand operated bilge pump.

On September 24, 1981, samples were collected at 25-cm depth intervals at sites PB-35, PB-50, PB-70, and PB-90 using a stainless steel drive point well screened for 20 cm and successively driven 25 cm deeper after each sample collection. Surface water samples were also collected from a Toll Road culvert and the diversion ditch surrounding the salt storage area.

Water chemistry determinations were made according to APHA (1975). An initial scan of metal concentrations was performed by the U.S. Geological Survey Central Laboratory

at Doraville, Georgia, by inductively coupled argon plasma atomic emission spectroscopy. Field specific conductance measurements were corrected to 25°C assuming a temperature coefficient of 0.025 (Smith, 1962). Corrections for pH (Sjörs, 1950) were not used because they resulted in numerous negative values for specific conductance. Mean pH values were determined from the mean hydrogen ion concentrations. Sodium and potassium were not analyzed in 1979 because of the lack of the necessary laboratory equipment.

Water chemistry data were grouped into separate yearly (June-October) categories because continuous sampling was precluded by winter freezing (which made the wells inoperable) and spring flooding. Statistical analyses were based on these yearly groups because the winter and spring months also presented the greatest opportunity for increase or decrease of deicing salt concentrations in the bog by salt-laden runoff or dilution, respectively.

The method of Powell and Jassby (1974) was used to calculate diffusion rates for ion movement from areas of high concentration to areas of lower concentration.

RESULTS

Specific Conductance

Mean specific conductance in shallow wells was different along the two transects, as shown in 1981 data (Figure 2). The 140 m unimpacted control transect had specific conductance values of about 62 $\mu\text{mhos/cm}$ along most of the transect length, although an increase to 79 $\mu\text{mhos/cm}$ was seen in the waters of the moat. By contrast, the impacted transect had values ranging from a low of 78 $\mu\text{mhos/cm}$ at PB-220s to a peak of 1948 $\mu\text{mhos/cm}$ at site PB-35s. A much lower specific conductance at site PB-0s is indicative of dilution in the moat that encompasses the first 30 m of the transect. Specific conductance readings in 1981 were higher in the shallow wells as far out as 140 m along the transect. It is apparent from Figure 1 that the salt load from the road-salt storage operation had not dissipated by 1981, but remained held within the peat mat, showing a clearly defined gradient from south to north.

Unimpacted Transect Chemistry

Water chemistry determinations for interstitial water samples collected from the unimpacted transect had very few significant variations between the three years of sampling. Mean concentrations (Table 1) were low for all parameters, with the mean specific conductance of 64 $\mu\text{mhos/cm}$ falling on the slightly minerotrophic end of the range reported by Verry (1975) as typical for bog watersheds that are isolated from regional groundwater flow.

Impacted Transect-Chloride

Elevated Cl concentrations in the shallow wells of the impacted transect were observed during all five years of

sampling, with yearly declines occurring between each of the first three years. The chloride concentrations were significantly lower (paired t-test, $\alpha = 0.05$) in each of these succeeding years in all shallow wells except PB-220s, which had low chloride concentrations in all years (Figure 3).

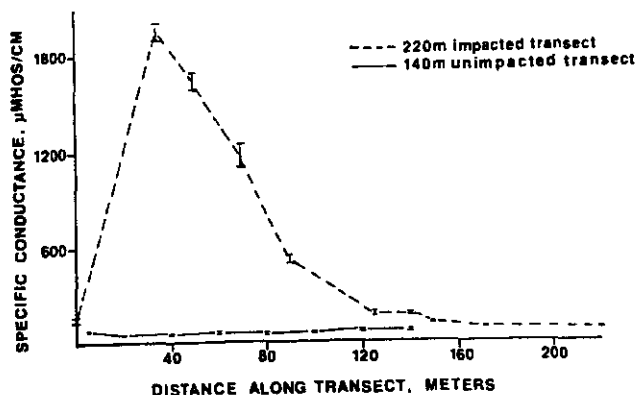


Figure 2. Mean Specific Conductance Along Impacted and Unimpacted Transects, Shallow Wells, 1981 (with standard errors).

TABLE 1. Mean Water Chemistry Determinations for all Interstitial Water Sampling Sites on Control Transect, 1980-1982.

Indicator	Mean	Standard Deviation	Number Samples
pH (units)	3.68	--	69
Sp. Conductance ($\mu\text{mhos/cm}$)	64.0	17.0	69
[concentration in mg/l]			
Acidity as CaCO_3	67.0	32.0	60
Alkalinity as CaCO_3	0.0	0.0	60
Chloride	5.9	2.7	76
Sodium	1.9	1.0	22
Potassium	0.9	0.4	22
Calcium	2.7	1.0	21
Magnesium	1.6	0.5	21

Chloride concentration differences between 1981 and 1982 were significant ($\alpha = 0.05$) for increases at PB-0s, PB-35s, and PB-50s and for declines at PB-70s and PB-90s. Between 1982 and 1983, significant increases occurred at PB-70s, PB-125s, PB-140s, and PB-150s, while a significant decline occurred at PB-35s. The increases in Cl over the last two years did not compensate for the much larger declines over the first three years and may merely reflect variations of a stabilized salt load. The overall observed trend of yearly decreases in chloride concentrations near the surface of the peat mat indicates that recovery of water chemistry from the impact of deicing salts was occurring there. Peak mean concentrations declined from 1215 mg/l at PB-50s in 1979

(206X enrichment over unimpacted transect) to 768 mg/l at PB-35s in 1980 to 512 mg/l at PB-35s in 1981. Increases at PB-50s were to 600 mg/l in 1982 and 610 mg/l in 1983.

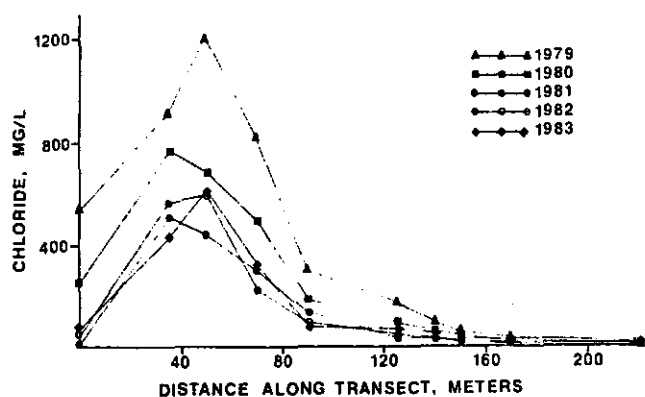


Figure 3. Mean Chloride Concentration Along Impacted Transect, Shallow Wells, 1979-83.

The yearly declines that did occur indicate that chloride ions were transported out of the half-meter of peat closest to the surface that was sampled by the shallow wells. The two wells adjacent to PB-125 had patterns of concentration declines similar to PB-125s, thus providing no evidence of horizontal migration. Vertical migration downward could be examined in part by looking at chloride concentrations for samples taken from the deep wells screened in the open water layer. Although yearly mean concentrations showed a gradient from south to north in all years (approximately 300 mg/l at PB-35d to 30 mg/l at PB-90d), the between-year changes showed no discernable trends. An apparent influx of fresh rainwater into this zone following an unusually large storm event in 1982 may have altered any yearly trends in the deep wells that might otherwise have been shown.

The vertical distribution of salt in the bog was determined from incremental samples taken at 25-cm intervals during September 1981. Progressing downward from the surface, Cl first increased and then decreased with depth through the peat mat (Figure 4). The maxima occurred just beneath the 0.5 m depth, except at PB-70 where it was at the 1 m depth. The type of peat had no observable influence on the distribution. Ionic concentrations were reduced sharply at the interface of the peat mat and the underlying open waters, and they increased with depth in the open waters within the secondary bog basin centered at 50 m along the transect.

Chloride concentrations at the four different depth wells at PB-50 (see Figure 4) were analyzed from 1981-83 to assess vertical ion migration. During the rainy sampling season of 1981 (69.4 cm precipitation), the shallow 0-0.5 m depth well underwent a general decline in Cl with time from 475 to 380 mg/l. This was accompanied by a general increase at the 0.5-1.5 m depth well from 860 to 990 mg/l. Actual numbers are not particularly meaningful because of the

unquantifiable dilution effect. However, the fluctuations through each year generally showed declines of the 0-0.5 m well to be accompanied by increases at the 0.5-1.5 m well, and vice versa, as correlated to specific rainfall events and dry periods.

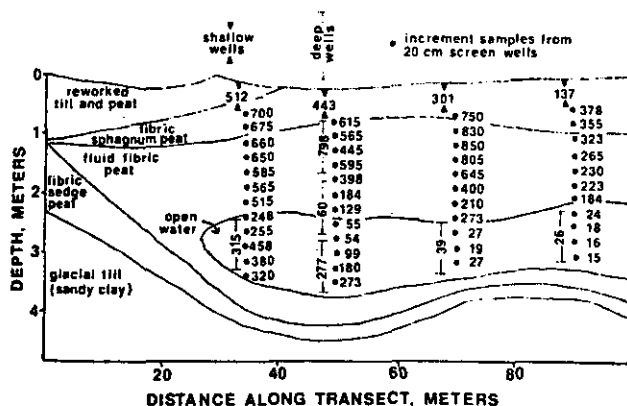


Figure 4. Chloride Concentration (mg/l) Profile Along Impacted Transect, Permanent Deep and Shallow Wells and Temporary Increment Wells, September 1981.

Cations

Enrichment of cations such as Na (100X), Ca (6X), Mg (5x), K (3X), Fe (2X), and Si (2X) at PB-50s was shown in an initial scan in 1979, as compared to site PB-220s. Concentrations of the four major cations were highest in shallow wells near the beginning of the impacted transect in all years sampled (Figure 5).

Sodium concentrations had the same characteristic pattern as chloride, although the 1980 peak of 468 mg/l (20.3 mM, 246X enrichment over unimpacted transect) was not quite as high as that of chloride (21.5 mM). The decline in Na concentrations from 1980 to 1981 was significant ($\alpha = t$ -tests). Sodium concentrations appeared to have stabilized from 1981-1983, although some significant changes occurred between years at individual sites.

The maximum enrichment factors for the other three major cations were much lower than that for Na. The characteristic distribution pattern was repeated for Ca concentrations in the shallow wells, with a peak of 39.5 mg/l at PB-35s in 1980 (15X enrichment over unimpacted transect). Calcium concentrations declined significantly between 1980 and 1981 in all shallow wells except PB-150s, PB-170s, and PB-220s. No consistent trends were observed for changes between the other years.

Potassium and magnesium concentrations in shallow wells were highest at the beginning of the transect. However, the magnitude of elevation was again substantially lower than for sodium (9X and 8X maximum enrichment over unimpacted transect, respectively). Potassium concentrations fluctuated at most sites between 1980 and 1982. In 1983, significant increases occurred at most sites on the first 140 m of the

transect. Magnesium concentrations fluctuated also, but significant decreases occurred at most sites on the first 70 m of the transect in both 1981 and 1983.

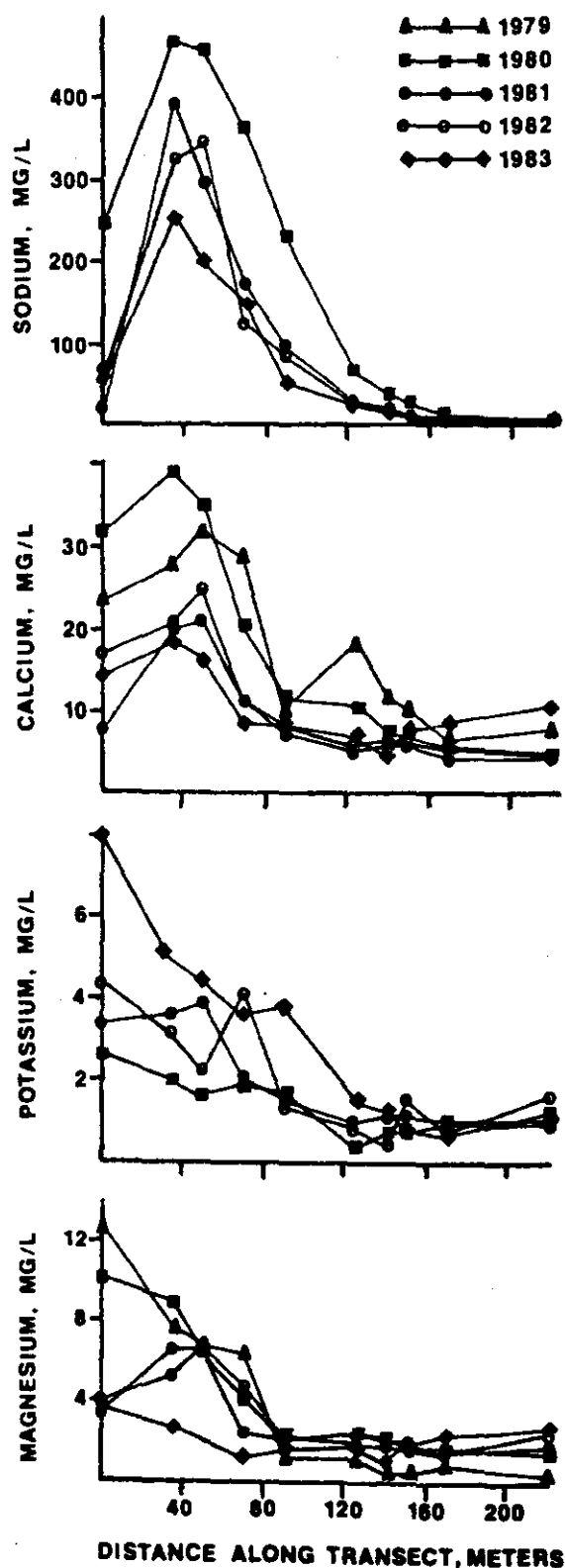


Figure 5. Mean Cation Concentrations Along Impacted Transect, Shallow Wells, 1979-1983.

The general pattern of decreasing Na and Ca concentrations from year to year near the surface prompted a look at deeper waters to detect possible increases there. Although enrichment was present, increases in Na and Ca were not found in successive years in the deep wells. In fact, there appeared to be a general decrease in concentrations, although not significant at all points. Potassium and magnesium concentrations in deep wells did increase generally from year to year, but this trend again was not significant at all points. The post-storm influx of rainwater appears to have influenced some of the cation concentration data in 1981.

The cation concentrations at the four different depth wells at PB-50 did not show yearly trends from which salt transport conclusions could be drawn. However, the vertical distribution of cations at the site (Table 2) does suggest that Ca was retained in the surface peats, Mg accumulated at depth, and Na and K were more evenly distributed between surface and subsurface peats.

TABLE 2. Mean Metal Concentrations in Waters from Four Well Depths at Site PB-50 in 1983.

Well Screen Depth (m)	Metal Concentrations (mg/l)			
	Na	Ca	K	Mg
0.0-0.5	200	16.8	4.4	2.1
0.5-1.5	240	5.2	8.4	0.4
1.5-2.5	128	5.1	6.0	0.9
2.5-3.5	42	6.6	4.8	1.4

pH and Buffering

On the impacted transect, two zones were observed in the shallow wells. Values of pH below 4.0 and poor buffering capacities (Figure 6) were found within the mat at PB-125s and beyond, while buffering capacities and pH were higher between PB-0s and PB-90s. There were no clear trends in the differences between years. The deep wells also had increases in pH, alkalinity, and acidity with proximity to the beginning of the transect but no yearly trends.

Contaminant Sources

Runoff from the Toll Road via the drop inlet-culvert system was the major continuing source of contamination following the construction of the protective dome over the salt pile in 1972. Mean specific conductance measurements during nonwinter months ranged from 10,398 $\mu\text{mhos/cm}$ in 1979 to 4738 $\mu\text{mhos/cm}$ in 1981, before the culvert was sealed. Overflow from the diversion ditch when dammed was a likely secondary source, with specific conductance in the ditch ranging from a mean of 8516 $\mu\text{mhos/cm}$ in 1979 to 3183 $\mu\text{mhos/cm}$ in 1980 before salt storage activities ceased. The only continuing source after 1982 was sheet flow from one lane of highway.

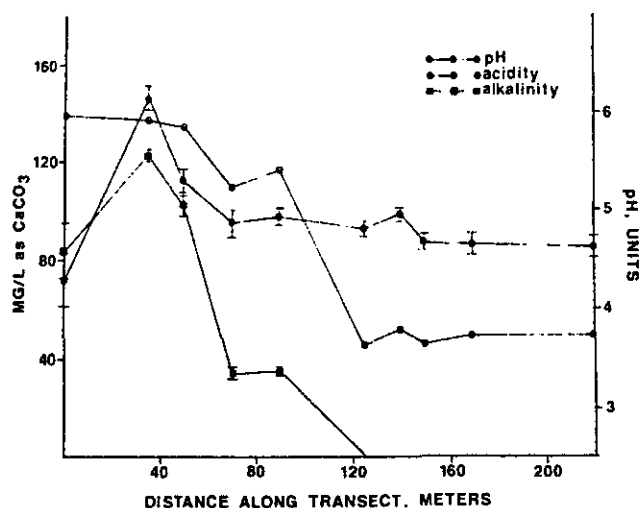


Figure 6. Mean pH, Acidity, and Alkalinity Along Impacted Transect, Shallow Wells, 1979-1983 (with standard errors).

Culvert and diversion ditch runoff both contained ion concentrations that were elevated above control transect levels. Peak means were 3388 mg/l Cl (574 X enrichment), 1125 mg/l Na (592X), 238 mg/l Ca (88X), 50 mg/l Mg (31X), and 11 mg/l K (12X).

DISCUSSION

Water Chemistry

Water chemistry determinations have shown that the salt load which entered Pinhook Bog accumulated in the surface peat and dissipated slowly, correlating with the severe localized impacts to the native flora that were observed. In contrast to the conclusions of Ten Ech (1975), chloride distribution in the interstitial waters of the surface peat presented a distinct pattern, with rather well-defined boundaries that coincided with the zone of observed impact to the vegetation. A similar pattern was observed for Na, with Ca, Mg, K, pH, and HCO_3 elevated, also. Runoff from the salt storage area and highway drainage were shown to be continuing sources of contamination.

Correlations can be drawn between some of the parameters that were elevated in the impacted zone, particularly Ca and Mg concentrations and pH (Sjörs, 1950; Gorham, 1956; Sepponen, *et al.*, 1978). It might be expected that Ca and Mg enter peatland systems in runoff largely as bicarbonates. In Pinhook Bog, the alkalinity at higher pH sites can generally be accounted for by the carbonates calculated on a molar basis for Ca and Mg at those sites. Thus, the addition of carbonate species (bicarbonate) of Ca and Mg from altered watershed drainage in the southern portion of the bog provided some buffering capacity to the waters, allowing corresponding elevations of pH.

Although fewer changes were observed in 1982 and 1983, declines in the concentrations of many of the enriched constituents were observed within the shallow wells during the first three years of sampling on the impacted transect. Within-year variability generally corresponded to the dilution and concentration effects of rainfall and drought. The only major sustained concentration changes occurred sometime during the November-May period each year when sampling could not be conducted from the frozen or flooded well casings. The peak chloride concentration observed during this study (1468 mg/l) occurred at site PB-50s on July 27, 1979. The mean concentration at that site for 1979 was 1215 mg/l. These concentrations may or may not be toxic to native plant species of the bog. However, since yearly declines have been shown, it is reasonable to assume that higher salt concentrations once existed in the plant root zone, thus increasing the likelihood of lethal effects on bog plants in the past.

Salt Transport

Changes in salt concentrations were probably caused by vertical transport of salt in response to snow-melt and heavy precipitation events in spring or evapotranspiration in dry summers (Boelter and Verry, 1977; Damman, 1978; Nichols and Brown, 1980; Hemond, 1980; Hooper and Morris, 1982). The yearly declines in the shallow wells between 1979 and 1981 indicate that salt ions were transported out of the surface peat layer, although the trend did not continue in 1982 and 1983 (to be addressed later). Figure 3 shows a lack of horizontal migration to the north or south. There is no evidence of horizontal migration to the east or west either, because concentration increases were not observed in the wells adjacent to PB-125. No additional component of advection or diffusion should exist in those directions. Sampling of deep wells along the impacted transect showed some increases in salt concentrations in the open water layer at some sites during those years, but the results were not conclusive.

Incremental sampling of the peat mat with depth detected layering of salt within the peat. The results did not show a smooth gradient of salt concentration, but this could be a result of channeling of water within the peat as a result of cracks (Dasberg and Neuman, 1977) or woody material (Galvin, 1976). Because salt concentrations were higher at depth in the peat mat than near the surface, the observed concentration decline in shallow wells between years was probably due to a downward transport of salt.

Downward transport of salt may be a function of two processes: molecular diffusion and water movement. In Pinhook Bog, transport by diffusion was assessed by assuming the water within the peat mat to be a homogeneous, mixed layer overlying a similarly homogenous layer represented by the open water beneath the mat. Calculations (Powell and Jassby, 1974) were performed on data from site PB-50 for changes from 1979-80 and 1980-81. Calculation of Cl transport across the boundary between the layers revealed that

molecular diffusion alone could account for the Cl depletion measured in the shallow wells between years. However, the actual increase in salt concentration measured in the deep wells was only about 2.5 percent of that expected from molecular diffusion calculations. Additionally, transport by the diffusion mechanism would be manifested in gradual declines in salt concentrations in the shallow wells throughout the year. Instead, concentrations remained quite stable during the June-October sampling period for each of the first three years. The major year-to-year concentration changes occurred between the last October sampling of each year and the first June sampling of the following year, the period when spring snow melt causes flooding of portions of the bog mat. These observations suggest that salt transport by water movement was a more dominant process than diffusion, contrary to the conclusions of Gorham and Hofstetter (1971). Also, the molecular diffusion rate calculations did not consider the effects of the surface water layer being held within a peat mass and may not be representative of actual diffusion rates.

Water movement through peat is partially controlled by the hydraulic conductivity of the peat (Boelter, 1964, 1965; Boelter and Verry, 1977; Dasberg and Neuman, 1977). Hydraulic conductivities of surface peats in Pinhook Bog average about 250×10^{-5} cm/sec (Wilcox, 1982), adequate to allow water movement to be the major influence on salt transport. In an isolated basin such as Pinhook Bog, precipitation and evapotranspiration control the movement of water through peat (Gorham and Hofstetter, 1971; Boelter and Verry, 1977; Hemond, 1980; Ivanov, 1981). Hemond (1980) concluded that vertical flow of water through peat was the major reaction to the downward driving force of precipitation and the upward force of evapotranspiration on a bog.

At Pinhook Bog, precipitation totals for the June-October sampling season and prior seven months were similar each year except for the wet year, 1981 (Table 3). Preseason and in-season totals show 1980 to be low and 1983 to be high in preseason precipitation. With few exceptions, substantial chloride concentration declines occurred at all sites between the last sampling date in one year and the first sampling date in the next, even in the dry year, 1980. This indicates that the preseason precipitation, especially winter snow-melt, was capable of transporting salt out of the surface peat zone. The June-October sampling season totals show some substantial differences in precipitation between years. In the wetter years

of 1980 and 1981, the precipitation served to maintain the lowered salt concentrations in the surface peat. In the drier years of 1982 and especially 1983, the upward force of evapotranspiration was able to overcome the downward force of percolating rainwater, and salt concentrations at the surface increased during the sampling season.

Other precipitation-related factors can influence salt concentration determinations, also. Daily, moderate rainfall events may equilibrate with evapotranspiration processes at the bog surface to result in little or no net water movement through the peat. Heavy, inundating rainfall events can create a head over the peat and may force downward water movement. The occurrence of heavy rainfall or drought just prior to individual sampling dates was observed to influence within-year concentration changes in Pinhook Bog. Another factor to be considered is that relative changes in salt concentration might become smaller in succeeding years as the overall concentration declines.

Fate of Salt Ions

Much of the sodium and chloride seems to have been transported outside of the region sampled by this study, apparently along flow paths in the deeper peats or the open water layer. Potassium was transported locally, but generally remained in the peat zone of the study area. Magnesium generally accumulated in deeper peats and the open water layer, and calcium was retained in the surface peats.

Anions such as Cl are highly mobile in organic soil systems (Brady, 1974), so Cl might be expected to pass completely through the peat layer. Some of the deeper peats and the open water layer seemed to accumulate Cl from year to year, but the magnitude could not account for the amount of Cl lost from the surface peat. This suggests that once Cl reached the deeper peats or open water layer, it was transported further out into the bog basin. Although this could not be demonstrated by the data from the deep wells (perhaps because of dilution), a more extensive deep well sampling network might help locate Cl in other portions of the bog basin. Transport out of the system via groundwater flow is unlikely because the bog basin is seated in a sandy clay glacial till (Wilcox, unpublished). Therefore, recharge into the regional aquifer is likely to be low in magnitude (Freeze and Cherry, 1979).

Cation movement through soils differs from anion movement because cations are absorbed to exchange sites on the

TABLE 3. Seasonal Precipitation Totals (cm) for LaPorte, Indiana, 1979-1983.*

Time Period	Year					Normal
	1979	1980	1981	1982	1983	
Presampling Season (November-May)	51.4	40.6	55.4	59.9	72.1	64.6
Sampling Season (June-October)	44.7	54.5	69.4	39.7	32.5	56.6
Preseason + Sampling Season	96.1	95.1	124.8	99.6	104.6	121.2

*From NOAA Climatological Data records.

colloidal complexes of the soil. Peat soils, in particular, have very high cation binding capacities (Brady, 1974). Passage of high concentrations of cations through the peat mat in Pinhook Bog would have resulted in a high percentage of the binding sites being occupied.

Compared to the other cations, Na is weakly retained on peat (Malmer and Sjörs, 1955; Scheffer and Schachtschabel, 1973; Boatman, *et al.*, 1975). Damman (1978) found Na to be easily exchangeable and to be the cation most rapidly and completely removed from the peat of a bog. The significant decreases in sodium concentration in the shallow wells of the impacted transect between 1980 and 1981 confirm that Na can be readily removed from the interstitial waters of the surface peat. However, an accumulation zone at greater depth did not occur. Decreases in the deep wells reflect either that dilution occurred from the influx of rainwater following a storm, that Na was complexed in the peat, or it was also removed from the study area.

Although increases in K were seen in various deep wells in different years, possibly reflecting leaching from plant tissue (Tukey, 1970), concentrations also increased in several shallow wells between years and were elevated at intermediate depths. Retention of K in *Sphagnum* moss (Brehm, 1968; Damman, 1978; Hemond, 1980) and selective transport to the surface during dry periods (Brehm, 1971) were probably responsible for the enrichment observed in shallow wells.

Magnesium concentrations declined significantly in several shallow wells of the impacted transect between 1980 and 1981 and again between 1982 and 1983, while they generally increased at all locations in the deep wells. These results coincide with the findings of Damman (1978), who attributed Mg loss to leaching and uptake by higher plants. Increases in aqueous Mg concentrations at increasing peat depths were also consistent with observations of Malmer and Sjörs (1955) and Hemond (1980), who demonstrated that the more humified peats at greater depths are less capable of retaining adsorbed cations. As a result, cations are released to the water as peats slowly decompose.

A consistent pattern of significant Ca concentration changes in the shallow wells occurred only in 1981. Of the four cations addressed in this study, Ca has been found to be the least mobile, being preferentially adsorbed and retained in the surface peat of bogs (Pakarinen, 1978; Damman, 1978; Bunzl, *et al.*, 1976). Calcium did not accumulate at intermediate depths at PB-50 and generally declined in most of the deep wells each year, in agreement with the observations of Damman (1978).

Fate of the Bog

The major source of contamination to Pinhook Bog was eliminated in 1972 when the salt storage pile was covered by a protective structure. Other sources were reduced when salt storage at the site was terminated in 1980 and the culvert was sealed in 1982. The remaining sheet flow from one lane of highway has not shown measurable effects on bog

water chemistry, but this may also be diverted if impacts are detected.

The decline in salt concentrations in the surface peat indicates that partial water chemistry recovery has occurred in the plant root zone. Since no data on salt concentrations in this zone exist for years prior to 1979, it is difficult to assess the rate at which this recovery has been occurring. In recent years with adequate precipitation occurring in major events and at the necessary intervals, chloride concentrations have declined by roughly a third each year. However, dry summers can result in subsequent increases which effectively stabilize the concentrations from year to year. Since long-term weather patterns are generally not predictable for localized areas, it would not seem fruitful to try to predict when natural bog water chemistry conditions might return to the entire impacted area. However, the data indicate that conditions suitable for growth of some of the resident bog plants have already returned to portions of the area. The general trends suggest that the recovery will continue on a slower basis for the remaining area.

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